DETERMINATION OF A SAFETY FACTOR OF A CAR WHEEL RIM USING FINITE ELEMENT ANALYSIS IN SOLIDWORKS

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Eleonora Desnica[1*], Mića Đurđev[1], Bojana Vaščić[1], Raul Turmanidze[2], Predrag Dašić[3]

[1]University of Novi Sad, Technical Faculty "Mihajlo Pupin", Zrenjanin, Serbia
[2]Georgian Technical University (GTU), Department of Production Technologies of Mechanical Engineering, Tbilisi, Georgia
[3]Academy of Professional Studies Sumadija, Kragujevac, Serbia

Abstract:
In this paper, a static analysis of car wheel rims made of different materials was performed with the aim of determining their safety factors. Selection of suitable car rims is very important since they are subject to different loads and have the role of transferring car mass both in static and dynamic conditions. Considering the high stresses that occur, car rims are made of strong and durable materials. For the purposes of static analysis and determination of safety factors of car rims, this research considered steel, aluminium, magnesium and carbon fibre rims. Based on the technical drawing of a car wheel rim, a solid model was created within the SolidWorks software, after which the calculation and simulation of loads and stresses is achieved. Afterwards, the safety factors of the car wheel rim made of four considered materials were determined using the finite element analysis (FEA). According to the obtained results regarding safety factors, it can be concluded that the carbon fibre wheel rims are the most suitable alternative for static conditions of exploitation.

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1. INTRODUCTION

The nature and the purpose of a product affects what material will be selected for its manufacturing. The selection of materials is influenced by design and manufacturing, availability of tools and machines, etc. Different materials can be used in design: organic, inorganic and synthetic. The material can determine the aesthetic quality of the product with its colour and texture, while the most suitable materials for a certain manufacturing technology are selected in design stage [1]. In the automotive industry, a large number of materials are used to build cars, primarily steel, iron, aluminium, rubber, glass, copper, composite materials and many others. In the last few decades, advances in development of these materials have led to advanced manufacturing and increased car safety. Car manufacturers strive to reduce car weight in order to increase speed and power, and thus improve its performance. Tyre-road friction also plays an important role in vehicle handling performance [2]. In addition, manufacturers aspire to increase safety in traffic, by selecting the suitable material with high toughness that would compensate energy during impact [3].

Appropriate selection of materials, dimensions, assemblies and machines in the automotive industry is achieved by CAD/CAM software. This software helped manufacturers change their approach to work, improve product design and expand work capabilities. Also, the use of this software helped companies to convey the concept of their products to potential investors who would encourage growth during the scheduled period. It enables companies to add new features to products through innovative solutions and achieve maximum user experience. Other key drivers expected to fuel

*CONTACT: Eleonora Desnica, e-mail: eleonora.desnica@tfzr.rs

market growth include awareness of technological developments, consumer demands, and market competition. It helped the car companies to significantly increase their profits in efficient and effective way [4,5].
This paper aims to present the concept of car wheel rims, their purpose, function and components. Then, the most common materials for car wheel rim manufacturing are presented, including steel, aluminium, carbon fibre, magnesium and titanium. The characteristics of wheels made of these materials, their advantages and disadvantages are presented. Among different CAD/CAM software, SolidWorks is selected for modelling the wheel rim, and then simulating loads and stresses using finite element analysis [6]. The static analysis of car wheel rims is considered with the aim of determining the safety factor of rims by considering different materials selected for manufacturing. Based on the obtained results, the most suitable and the safest car wheel rim for static conditions is selected.

2. CAR WHEEL RIMS

In addition to improving the aesthetic appearance of the car, more emphasis should be placed on how significant the car rims are. Rims as the load-bearing parts of car tyres play a key role in keeping the tyre intact and undamaged. They are available in various sizes and designs. Therefore, it is important to emphasize the differences between the rims, the ways they affect the efficiency and the working principle in cars. Rims provide leverage and reduce friction when the car moves. They are necessary for all cars, including commercial and passenger vehicles. Rims determine whether the car will perform well and whether the drive will be comfortable. Hence, the selection of the appropriate rims for the car is crucial for best performance of the car [7]. Rim size can give the car an innovative aesthetic look. Most often, vehicles with smaller wheels are classified as low-profile. It is important to note that changing the size of car rims has a great impact, primarily on braking, handling, acceleration, alignment and speedometer calibration. Wheel size also includes its diameter, width and offset [7, 8]. A schematic representation of a single car wheel rim is given in Fig. 1. Wheels can be considered the crucial transfer components between a tyre and a vehicle [9]. There are several elements that compose a car wheel. The nomenclature is given below [10-13]: Rim – a part on which the tyre is placed; Disc – a part of the rim that is attached to the axle hub; Offset – a space between the mounting surface of the wheel where it is attached to the hub and the centre line; Flange: a part of the rim that holds two tyre beds; Bead Seat: a part of the rim that holds the tyre in a radial direction; Hump - a part that prevents the tyre from sliding off the rim when the vehicle is in motion; Hub Hole - a part of the rim with depth and width that facilitates the installation and removal of the tyre from the rim.

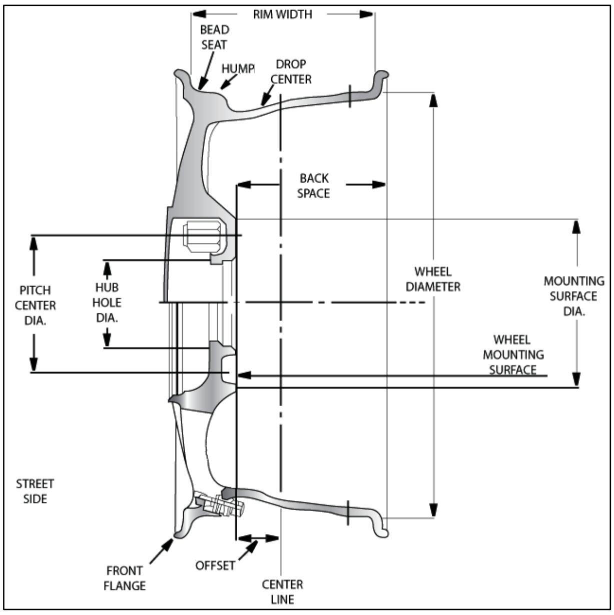

Fig. 1. A car wheel rim [14]

2.1. Function and requirements of a car wheel rim

In its basic form, the rim is a transferring element between the tyres and the vehicle. The following functions of the rim are highlighted: torque transmission (braking and acceleration), supporting mass (supports the mass of the vehicle's engine), adding mass (damped mass for a more comfortable drive), heat dissipation (due to braking), shock absorption (road hazards), energy saving (potential energy).

Depending on the application of car rims (sports cars, passenger and commercial vehicles, etc.), design requirements also change. Wheel design for agricultural vehicles are far different from passenger vehicles, with the basic design requirements being similar.

Basic requirements for any vehicle rim include the following mechanical characteristics: structural Stiffness, static strength (deformation under all types of loads), fatigue strength, and impact strength.

Inadequate design and material lead to damage and weight reduction of the vehicle which is a major problem in the automotive industry. Nowadays, the most common materials for manufacturing of car rims are aluminium alloy and steel replaced by epoxy materials made of carbon fibre E-Glass [10]. Steel is often used due to its lower cost and its lower density than aluminium. Also, carbon fibres have higher strength compared to steel alloys and aluminium alloys [15, 16].

3. CAR RIM MATERIALS

The selection of material for car wheels is a very important task. Wheels carry the entire weight of the car and are affected not only by vertical forces, but also by uneven and impact forces resulting from driving, braking, bumps in the road, turning and all impacts of a rough road. A car wheel is mostly made of steel, aluminium or magnesium alloy. However, many different materials for wheel rims have been considered so far. Agrawal et al. [17] performed statistical analysis of wheel rims made of eight different materials, including aluminium alloy, structural steel, Kevlar, s-glass, e-glass fibre, basalt fibre, carbon fibre and high-strength low alloy steel. Bastin et al [18] took steel alloy, aluminium, magnesium and forged steel for analysis in Abaqus software. Mereuta [19] considered four different materials for static analysis in Inventor software: steel, aluminium, magnesium and titanium. Similarly, in this study, we adopted four standard materials, steel, aluminium, carbon fibre and magnesium.

3.1. Steel car rims

As far as steel wheels are concerned, the selection of appropriate material depend largely on the specification regarding operational strength and weight requirements [8]. All steel wheels consist of two pressed components, the rim and the wheel disc, which are welded together. Rim dimensions, shape and condition must be appropriate to fit the particular tyre required for the vehicle. The disc wheel serves as a support between the hub of the vehicle and the rim. Dimensions, shape and position of the rim must correspond to the design of the wheel hub and the geometry of the suspension of the vehicle on which it is mounted. The main advantages of steel wheels are: low cost, flexibility, good shock absorption and deformation protection, as well as simple and cheap repair in case of bending. The main disadvantage of steel wheels is their weight and poor resistance to corrosion.

3.2. Aluminium car rims

Light metal wheels are mostly made of aluminium or magnesium alloys. Aluminium wheels are offered as cast, forged, metal plate, or hybrid wheels [8]. The use of aluminium in modern cars began in the early seventies of the last century, when, under the pressure of the oil crisis, car manufacturers around the world were forced to reduce the weight of cars in order to achieve the lowest possible fuel consumption. Aluminium is used to make a large number of car parts including the body, chassis, wheels and many others. Special attention is paid to the use of aluminium for car wheels, which represents almost 15% of the average aluminium content in passenger cars. Important features of aluminium rims are high rigidity, good static performance, low weight, corrosion resistance and others.

3.3. Carbon fibre car rims

Due to low density, high strength and high stiffness, excellent resistance to impact and corrosion, CFRP (Carbon fibre reinforced polymers) are widely applicable materials in various building components. Also, materials such as Kevlar, fiberglass, and aluminium can be used along with carbon fibre. Carbon fibre reinforced polymers (CFRP) are produced from carbon fibre and resin under specific conditions. Especially in the field of astronautics and aviation, CFRPs show their potential. This material has numerous advantages: weight reduction, integration and reduction of car parts, crash protection, durability and strength [10, 15, 16, 20-22].

3.4. Magnesium car rims

Magnesium is widely used in sports cars and is a preferred variant compared to other materials because of its low density [23]. Every gram reduced affects the speed of the vehicle. This is a result of the slightly better strength-to-weight ratio that magnesium alloys have compared to aluminium alloys. The weight of the rim can be reduced by approximately 30% compared to the aluminium rim. Strong and fire-resistant magnesium alloys are obtained by adding Si, Mn, Al, Zn and other elements. The main advantages of rims made of magnesium are: weight, heat, aesthetics, and price [24].

4. MATERIALS AND METHODS

In order to analyse the safety factor of different materials of car rims, the methodological concept of this study has two parts. Firstly, the necessary calculations of weight, forces and stresses are made, and afterwards, the static analysis is performed using the finite element analysis.

SolidWorks software was selected in this research. This software includes a wide range of functions such as tools for design validation or reverse engineering. It is usually used to make industrial components in a practical and detailed way [25].

As part of this research to develop a 3D model of the car rim, a technical drawing of the rim presented in Fig. 2 is considered. Based on the technical drawing, a 3D model of the rim was obtained. Rendered models regarding four different materials are shown in Fig. 3. The obtained model was used as an input for the next stage which considers the finite element analysis for simulating loads and deformations based on the selected surfaces.

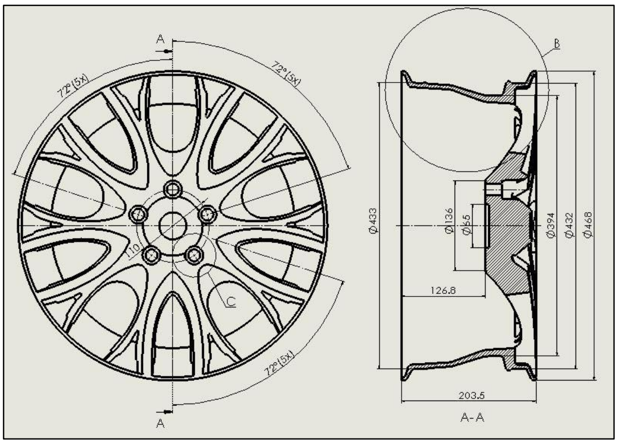

Fig. 2. Technical drawing of the proposed car wheel rim

a)

b)

c)

d)

Fig. 3. 3D model of a car wheel rim: a) steel, b) carbon fiber, c) magnesium and d) aluminum

4.1. Methodological concept of the static analysis using FEA

In the paper, a simulation of the load of the car's mass and the pressure of the tyre on the rim, which is made of four different materials: steel, aluminium, magnesium and carbon fibre, was carried out. Conditions regarding the car rim, rim dimensions and loads are identical for all tested materials. For research purposes, a static finite element analysis was used, which was carried out in the SolidWorks. As far as the application of the FEA in car wheel design is concerned, various research studies have been proposed so far. Parihar and Chakraborty [26] proposed FEA for dynamic analysis of car wheel rim in ANSYS software. Stress, shear stress and deformation are considered as dynamic parameters and magnesium alloy, aluminium alloy and steel S-7 as existing materials of wheel rim. Agrawal et al. [17] performed static structural analysis of modelled wheel rim using SolidWorks and ANSYS software. The analysis is carried out for tyre inflation pressure, rotational velocity and moment condition and the most suitable material among six alternatives is obtained according to equivalent stress, equivalent strain and total deformation of the rim. Bastin et al. [18] used SolidWorks for modelling standard automotive wheel rim and ABAQUS software for FEA static load analysis by considering four different materials of wheel rim. The displacement and the maximal principal stress were noted. Hunady et al. [27] applied FEM analysis of an aluminium wheel of a passenger car. They performed the linear static analysis and the fatigue life analysis. Firstly, the objective was to determine the stress state under the bending force, and later, the aim was to verify the durability of the wheel for two load levels. The fatigue life was higher in both dynamic tests. In terms of strength and durability, the aluminium wheel proved to be a satisfactory option. Abdullah et al. [28] in their review pointed out the applications of FEA models for fatigue life predictions of automotive components. In this study, authors focused on the static analysis using FEA. Prabowo et al. [29] used Fusion360 and ANSYS software to design and simulate radial fatigue dynamic test of rim wheels. They discovered how the variations in thickness, geometry, and material affect the displacement of the safety factor and as well as how changes in safety factor affect mass and cost reduction.

After modelling the car rim design in the SolidWorks, the simulation was performed. Within the simulation, determination of the load on the rim of motor vehicles and trailers using the FEA method was considered. By analysing the components of the wheel assembly, critical loads can be determined. Also, the points at which deformations of the rim material that occur can be obtained. The aim of the simulation is to determine whether the modelled design of the rim meets the prescribed conditions of exploitation in terms of load and stress before its actual production. In this way, subsequent changes and problems during production are eliminated, the time from conceptual solution to the finished product is reduced, and the total cost of the production cycle is reduced. The result is a more reliable product that can be safely used in practical conditions [30, 31].

4.2. Methodological concept of a car rim calculation

For the purpose of this study, the following initial parameters were considered:

- car mass $m = 2850\ kg$, and
- operating stress $\sigma_T = 2{,}4\ \cdot 10^2\ N/mm^2$.

Accordingly, in order to perform static analysis, the research methodology was prepared.

Data preparation

The car is assumed to be in a static state, i.e., pressure of the car weight and pressure of the tyre on the car rim in a resting state are assumed.

The weight of the car is calculated in the following way:

$$Q = m \cdot g \qquad (1)$$

Assuming that the car weight is evenly distributed on all four wheels, the weight acting on a single wheel is the vertical reaction of the ground and can be calculated with this equation:

$$F_z = Q/4 \qquad (2)$$

The radial load on each wheel exists due to the mass of the car. In the static condition for radial load, it is considered that the weight is evenly distributed along all wheels.

Tyre pressure that constantly acts on the rim is p_g =2.4 bar.

Lateral force on the rim based on the adopted wheel dimension 195/45 R 17 can be calculated using the following equation [27]:

$$r_1 = \frac{432}{2} = 216\ mm = 0.216\ m; \qquad (3)$$

$$r_2 = r_1 + 45 = 261\ mm = 0.261 m \qquad (4)$$

$$F_S = \frac{pg \cdot \pi \cdot (r_2^2 - r_1^2)}{2} \qquad (5)$$

Where r_1 stands for the radius of a 17-inch wheel rim in millimetres, while r_2 is the sum of radius r_1 and tyre aspect ratio.

The conditions of the environment where the car is located are ideal. Rim dimensions 195/45 R 17.

All screw holes are fixed, i.e. translation and rotation in x, y and z directions are zero.

The properties of the materials proposed in the paper are shown in Table 1.

Table 1. Characteristics of analysed materials

Properties	Steel	Aluminium	Magnesium	Carbon fibre
Density (kg/m^3)	7,800	2,800	1,800	1,800
Young's modulus of elasticity (E) (N/mm^2)	$2.34\cdot10^5$	$72\cdot10^3$	$45\cdot10^3$	$2.9\cdot10^5$
Poisson's ratio (-)	0.3	0.33	0.29	0.2
Critical stress (N/mm^2)	235	160	130	2500

Within the presented methodology, the calculated values of the car rim using Equations 1-5 are shown in Table 2.

Table 2. Calculated values of the car rim

Calculated values	Values
Car weight - Q (N)	27,958.50
Vertical reaction of the ground - F_z (N)	6,989.63
Tyre pressure that constantly acts on the rim - p_g (N/m^2)	240,000.00
Lateral force on the rim - F_s (N)	8,088.00

Car wheel rim mesh is generated using SolidWorks software and is shown in Fig. 4.

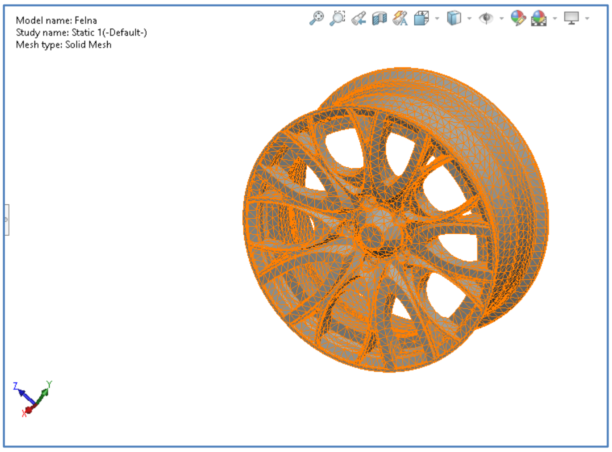

Fig. 4. Creating mesh of a car wheel rim design

Fig. 5 shows the procedure for placing a fixed support at the place of the opening for screwing the rim onto the car, while Fig. 6 shows the way in which the loads F_z were introduced to the observed 3D model of the rim.

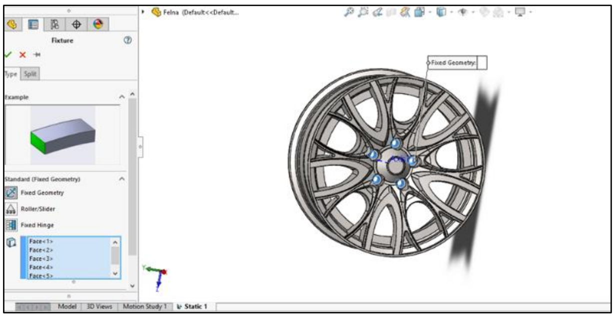

Fig. 5. Fixed support placement at the screw hole

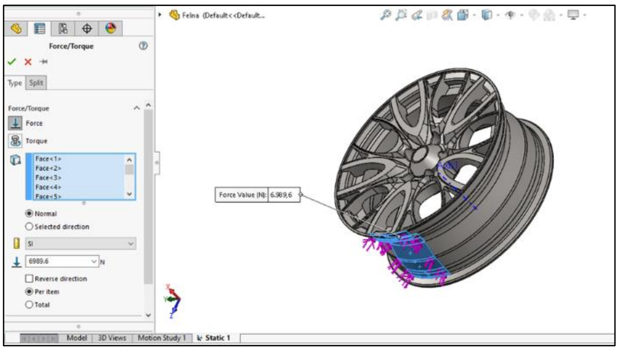

Fig. 6. Applying the load Fz on the 3D model

Fig. 7, 8 and 9 show the environment in SolidWorks in which the analysis of the finite elements of the car rim was performed based on the given loads. The simulation in these figures consider steel wheel rim material only. The obtained yield strength for this alternative material equals 235 MPa.

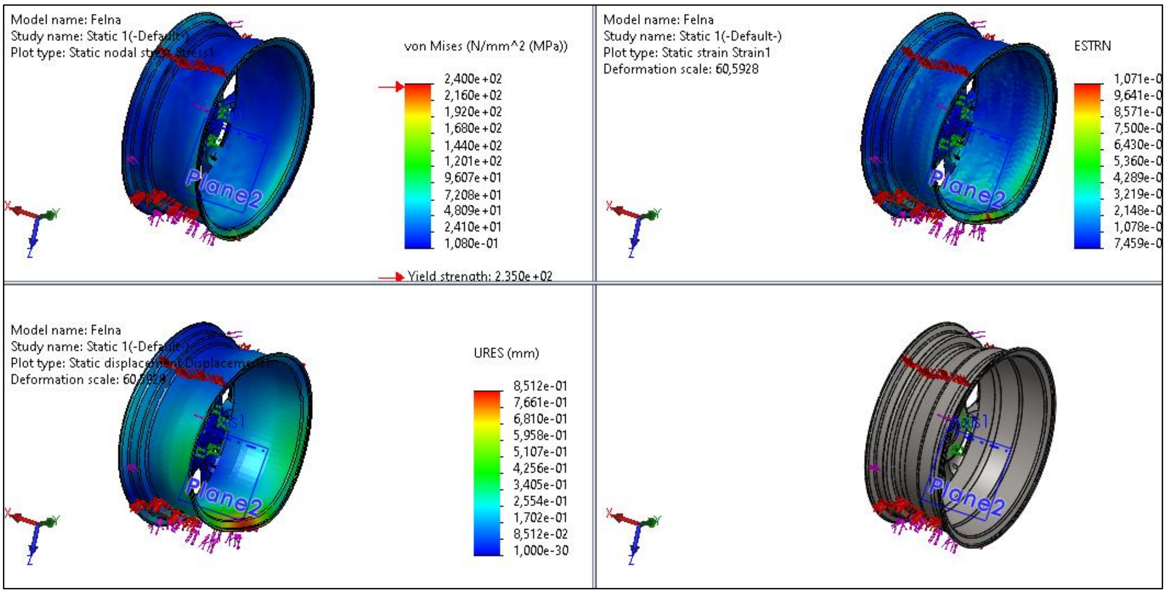

Fig. 7. Finite element analysis (static analysis) of a car rim

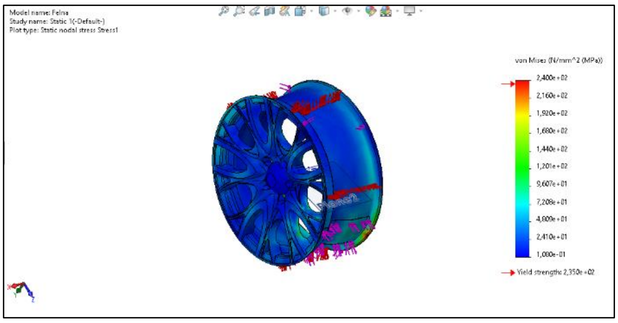

Fig. 8. Results and analysis of the stress state of the rim

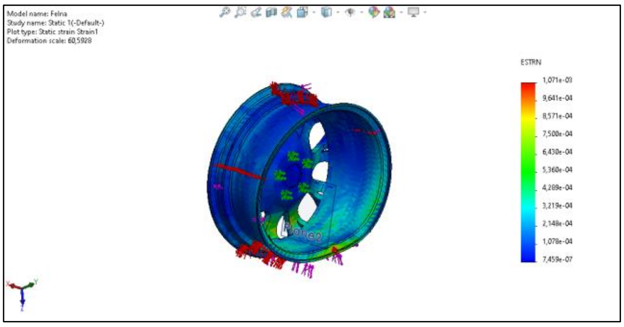

Fig. 9. Simulation of the rim deformation due to given load

5. RESULTS AND DISCUSSION

The car wheel rim capabilities to withstand various types of loads is checked. The analysis is performed on the basis of the safety factor against critical phenomena, which would prevent the correct functioning of the machine component. The safety degree is defined by the ratio of critical and working stress over equation 6.

A critical load is a load that causes critical phenomena in the machine component, such as large (unallowable) elastic deformations, plastic deformations, static destruction - tearing, dynamic destruction - fracture due to fatigue, etc. It is, therefore, a load that disables the component from performing its function correctly. A load that does not cause critical phenomena in the machine part, i.e. under which the machine part performs its function correctly is called working load. The safety factor mathematically shows how much work load should be increased, in order for critical phenomena to appear in the machine component. When the value of the workload becomes equal to the critical value, the value of the safety factor is S=1. In this case, safety of a machine part cannot be granted which then leads to critical phenomena.
After the results of the finite element analysis, the safety factor can be obtained using the following mathematical expression:

$$S = \frac{\sigma}{\sigma_T} \tag{6}$$

Table 3 provides values of critical stress and safety factors for each analyzed material separately:

Table 3. Critical stress and safety factor of the analyzed materials

Material	Examined value	
	Critical stress - σ (N/mm²)	Safety factor - S (-)
Steel	235	0.98
Aluminium	160	0.67
Magnesium	130	0.54
Carbon fibre	2500	10.42

From the obtained calculations for each of the considered materials, it can be noticed that the most suitable material for application in this particular case is convincingly carbon fibre. Steel, along with magnesium and aluminium, proved to be an unsuitable material with a safety factor of S < 1, which does not meet the requirements for safe implementation of the car rim in static conditions.

6. CONCLUSION

In this paper, an analysis of the safety factor of car rims made of four different materials was performed. The materials that were taken for the analysis are steel, aluminium, magnesium and carbon fibre. As a starting point, a 3D model of a car rim was designed in SolidWorks. Afterwards, the FEA analysis of loads and stresses was carried out within the SolidWorks. After determining the working stresses obtained by simulating the tyre pressure, the car weight and the lateral load on the 17-inch car rim, the safety factor for the considered materials was determined. Based on the static analysis, it was determined that carbon fibre is the best alternative for the car rims manufacture based on the safety factor in static conditions which amounts 10.42. Future research in this field would be directed towards dynamic analysis in order to predict problems that may arise in the construction of the car rim, as well as what conclusions are reached when changing from a state of rest to a state of motion and vice versa.

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